TECHNICAL REPORT TR-RD-SS-90-4

THE RELEVANCE OF THE DE BROGLIE RELATION TO THE HUGONIOT ELASTIC LIMIT (HEL) OF SHOCK LOADED SOLID MATERIALS

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Aeroballistics Analysis Branch
Systems Simulation and Development Directorate
Research, Development, and Engineering Center

MARCH 1990

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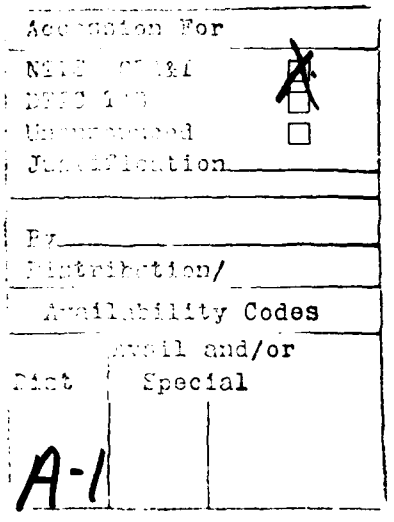

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Under moderate shock loading (a few kilobars) where Elastic-Plastic Shock Phenomena (EPSP) occur in solid materials, two stress waves are created. The first one is essentially an elastic wave and has become known as the Hugoniot Elastic Limit (HEL). The HEL particle velocity, Up_{HEL}, can be closely related to the De Broglie particle momentum wave velocity, $V_1 = h/(2md_1)$, where, h is Planck's constant, m is the mass of an atom, and d_1 is the closest distance between atoms in the structure. Classic EPSP test data for iron, aluminum alloys (2024, 6061), and pressed TNT are compared to computed values of V_1 and $2V_1$. Qualitative remarks with respect to particle stability are made which are based primarily on Fitzgerald's analysis ([17]), Chapter 3.)

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I. INTRODUCTION

Many solid materials under moderate shock loading exhibit a two–wave structure where the first one is essentially an elastic wave followed by a slower plastic deformation wave front. References [1] through [10] contain experimental data which illustrate this elastic–plastic–shock phenomena (EPSP). Selected wave and particle velocity results from this classic experimental information for iron, aluminum alloys, and pressed TNT are shown in Figures 1 through 6. Various theoretical aspects of EPSP are described in References [7] through [14].

The elastic wave generated under EPSP conditions is called the Hugoniot Elastic Limit (HEL) to distinguish it from a dynamic elastic limit which could occur from less severe transient load conditions [13]. It is noted in reference [12], page 191, that the HEL condition can produce the same effect as a phase transition. That is, an additional wave is formed.

The main purpose of the present report is to provide evidence that the HEL particle velocity, U_{PHEL}, is fundamentally determined (or essentially limited) by the De Broglie momentum velocity–wave length relation which applies for any type of particle motion (Reference [15], page 479; and Reference [16], page 433). Consequently, new insight with respect to the EPSP is provided by the fact that experimentally observed steady state, or stable, values of U_{PHEL} compare favorably with the De Broglie velocity, V_1. V_1 is computed for an unperturbed atomic lattice (see Section II). These comparisons are shown herein for shock loaded iron, aluminum alloys, and TNT, which exhibit EPSP and HEL stress waves.

II. THE De BROGLIE PARTICLE VELOCITY, $V_1 = H/(2MD_1)$

Fitzgerald ([17], Chapters 1 and 3) delineated the importance of the De Broglie momentum wave–wave length particle velocity, V_1, with regard to impacted solid material behavior. The De Broglie velocity, V_1, is:

$$V_1 = \frac{h}{2md_1} = \frac{h}{m\lambda_1} \tag{1}$$

Where:

V_1 = Limiting particle velocity which can occur without permanent lattice distortion (plastic flow); or the limit particle propagation velocity in a stationary lattice. Units are cm/sec or km/sec

h = Planck's Constant

= $6.6262 * 10^{-27}$ (gram)(cm^2)/sec

m = Mass of one atom, grams

d_1 = Closest distance between the atoms in a crystal lattice, or the atomic spacing in a slip direction, units are cm or angstroms, A°, (1 A° = 10^{-8} cm)

λ_1 = 2 d_1 = wave length associated with the momentum, mV_1. It is the shortest wave length possible in an undistorted lattice or stationary lattice, cm or A°.

Table 1 lists V_1 information for iron, aluminum, and TNT (ρ_o = 1.648 g/cc). The values for iron and aluminum are from Reference [17]. V_1 for aluminum was employed for the aluminum alloys (2024 and 6061) since they contain a very high percentage of aluminum. For TNT, an average value of the mass (m_{av}) of an atom and the average distance between atoms (d_{1av}) was computed in the manner outlined in Reference [18]. These average values (m_{av} and d_{1av}) were employed in Eq. (1) to compute V_1 for TNT.

Table 2 lists longitudinal elastic wave velocity, C_L, information for the materials considered in this report. Also shown in Table 2 is the elastic wave pressure, P_{v1}, corresponding to the wave velocity, C_L, and the particle velocity, V_1. This is given by:

$$P_{v1} = \rho_o C_L V_1 \tag{2}$$

where ρ_o is the material density (grams/cc).

TABLE 1. Tabulation of V_1 for Iron, Aluminum, and TNT.

TABULATION OF V_1 FOR IRON, ALUMINUM, AND TNT							
Material	ρ_0	m	d_1	V_1	$2V_1$	$\frac{V_1}{2}$	source
~	g/cc	grams x 10^{-23}	A^0 ($10^{-8}cm$)	km/sec	km/sec	km/sec	~
Iron	7.84	9.27	2.48	0.0144	0.0288	0.0072	[17]
Aluminum	2.70	4.48	2.86	0.0258	0.0516	0.0129	[17]
TNT (pressed)	1.648	1.80	2.22	0.0832	0.1664	0.0416	[18], present

TABLE 2. Tabulation of C_L and Pv_1.

TABULATION OF C_L AND P_{V1}				
Material	ρo	C_L	V_1	Pv_1
~	g/cc	km/sec	km/sec	kbars
Iron	7.84	6.04 [2]	0.0144	6.82
2024 –T4	2.70	6.41 [7]	0.0258	4.46
6061 –T6	2.70	6.23 [8]	0.0258	4.34
TNT	1.648	2.798 [10]	0.0832	3.84

$$P_{V1} = \rho_0 C_L V_1 = \left(\frac{G}{cc}\right)\left(\frac{cm}{\mu - \sec}\right)\left(\frac{cm}{\mu - \sec}\right) = MBARS$$

$$P(KBARS) = 10^3 P(MBARS)$$

$$1 \; KBAR = 14,504.0 \; PSI$$

III. FITZGERALD'S PARTICLE VELOCITY STABILITY CRITERIA

Fitzgerald, utilizing his concept of reversed lattice motion ([17], Chapter 3) shows that particle velocities from approximately 0.50 V_1 to 0.75 V_1 are in an unstable region and can jump to values higher than V_1. Fitzgerald cites experimental results from Professor Bell and co–workers at Johns Hopkins University which support the analytical prediction.

Particle velocities in the immediate region around V_1 appear to be stable.

In addition, Fitzgerald also showed $2V_1$ was an important unstable velocity where excessive distortion would occur. This analytical result also compared favorably with experimental results obtained by Bell and co–workers for aluminum and copper. These experimental data were acquired from end–to–end cylindrical rod impact via diffraction grating instrumentation.

Professor Bell summarizes his results in Reference [21] and lists three critical or transition particle velocities which were experimentally discovered in pure aluminum. They are listed as follows and compared to V_1 for aluminum (2580 cm/sec from Reference [17])

$$V_{cr1} = 1478 \text{ cm/sec} = 0.573\ V_1 \sim 0.6\ V_1$$

$$V_{cr2} = 3350 \text{ cm/sec} = 1.298\ V_1 \sim 1.3\ V_1$$

$$V_{cr3} = 5080 \text{ cm/sec} = 1.969\ V_1 \sim 2.0\ V_1$$

The comparison is remarkably good, particularly for V_{CR1} and V_{CR3}.

Thus there are three important velocity regions:

1. 0.50 V_1 to 0.75 V_1; unstable, may jump to a magnitude greater than V_1.

2. V_1 vicinity; apparently stable.

3. V_1 to $2V_1$; unstable, particle velocities in this region will approach V_1 under "long term" operating conditions. Ample time is necessary to allow particle momentum sharing with a sufficient number of lattice masses, (see [17], pages 72 to 74). This, by definition, is a relaxation time.

IV. EXPERIMENTAL HEL U_{PHEL} DATA AND COMPARISON WITH V_1 MAGNITUDES

A. Iron

References [1] through [6] document experimental investigations of shocked iron. Figure 1 depicts experimental data points for HEL wave velocities as a function of the particle velocity. No actual data points for the plastic wave data are shown. Instead, a recommended [6] linear fit to the plastic wave velocity is illustrated. Only a few data points (with considerable scatter) were available for particle velocities less than 0.06 km/sec and the primary focus of the present study was the elastic wave behavior.

Various investigators found that the HEL for iron depended on the test specimen thickness. Figure 2 illustrates experimental U_{PHEL} data as a function of test specimen thickness. A very corroborative data point in Figure 2 was found in Figure 14 of Reference [19]. Reference [19] is an historical review article concerning shock physics investigations performed at Los Alamos National Laboratory. The initial particle velocity (free surface velocity divided by 2) was practically identical to V_1 for this specimen thickness (24.7 mm).

V_1 and $2V_1$ indicators for iron are shown in Figures 1 and 2. The experimental values for U_{PHEL} vary from approximately 0.5 V_1 to 2.4 V_1. Most of the U_{PHEL} magnitudes lie between V_1 and $2V_1$.

As shown in Figure 2, $U_{PHEL} \approx 2V_1$ for the thin specimen and U_{PHEL} approaches V_1 for thicker specimen. Thus, the initially overdriven "elastic" wave U_{PHEL} is not stable near $2V_1$. It decays or relaxes to a stable value (V_1) provided that the sufficient time (travel distance or specimen thickness) is available. This experimentally observed behavior corroborates remarks made in Section III with respect to the unstable region 3 where $V_1 < Up < 2V_1$.

See also the initial remarks in Section II of Reference [20] with respect to the asymptotic particle velocity decay exhibited by the data in Figure 2. This reference employs dislocation theory to model the observed phenomena.

An earlier phenomenological model for the relaxation time, τ, is developed in Reference [4]. Reference [4] equations for τ and specimen thickness, L, can be written in terms of V_1 and $2V_1$. This is because 0.0140 and 0.0280 mm/μ–sec appear as constants in the equations and V_1 and $2V_1$ are equal to 0.0144 and 0.0288 mm/μ–sec respectively. The significance of the number 0.0140 mm/μ–sec is that it was the observed steady state particle velocity, which is shown in Figure 2 to be V_1.

B. Aluminum Alloys

1. 2024 Alloy

Reference [7] documents Fowles' classic experimental and theoretical study of EPSP for both hard and soft 2024 aluminum alloy specimens. Initial and final values of the elastic wave free surface velocities (2 • UPHEL) were tabulated in Reference [7]. These UPHEL data are plotted in Figure 3 which apparently indicates that over–driven transient behavior was exhibited by the "elastic" wave particle velocity data for both hard and soft specimens. However, unlike iron, none of the UPHEL magnitudes exceed $2V_1$. The general relevance of the De Broglie velocity, V_1, to UPHEL behavior is substantiated by these data for 2024 aluminum alloy. Certainly, the UPHEL magnitudes compare reasonably well with V_1.

2. 6061–T6 Alloy

Experimental EPSP results for 6061–T6 aluminum alloy are documented in References [8] and [9]. Elastic and plastic wave velocities and corresponding particle velocity information from reference [8] is graphically illustrated in Figure 4. UPHEL data from Reference [9] are plotted versus specimen thickness in Figure 5. This UPHEL information was obtained from the initial step rise of the transient free surface velocity (U_{fs}) data in Figures 4, 5, 6, and 7 of Reference [9]. The initial U_{fs} was carefully scaled from these figures and then UPHEL was computed via the well known relation:

$$Up = U_{fs}/2 \tag{3}$$

As illustrated in Figure 4 (Reference [8] data), the particle velocities for elastic waves (with no following plastic wave) do not exceed V_1 by more than approximately twenty percent. This indicates that the limiting particle velocity for a true elastic wave was essentially V_1. When the loading increased to until EPSP began, the "elastic" wave velocity and particle velocity behaved in an erratic manner. This may be indicative of the instability that could be expected where $V_1 < U_{PHEL} < 2V_1$.

Compared to iron (Figure 2), UPHEL for 6061–T6 (Figure 5) exhibits very weak dependence on the specimen thickness (or time). The trend is that shown by the data collected from Figure 4 of Reference 9. UPHEL magnitudes vary from about 0.80 V_1 to 1.30 V_1. Thus for a rather wide range of specimen thicknesses and input shock pressures (P_{max}), UPHEL was within thirty percent of V_1. The asymptotic stable value of UPHEL was approximately 0.85 V_1, or essentially V_1.

These HEL data for 6061–T6 confirm the importance of V_1 and substantiate the remarks in Section III with respect to particle velocity stability when $V_1 < U_{PHEL} < 2V_1$.

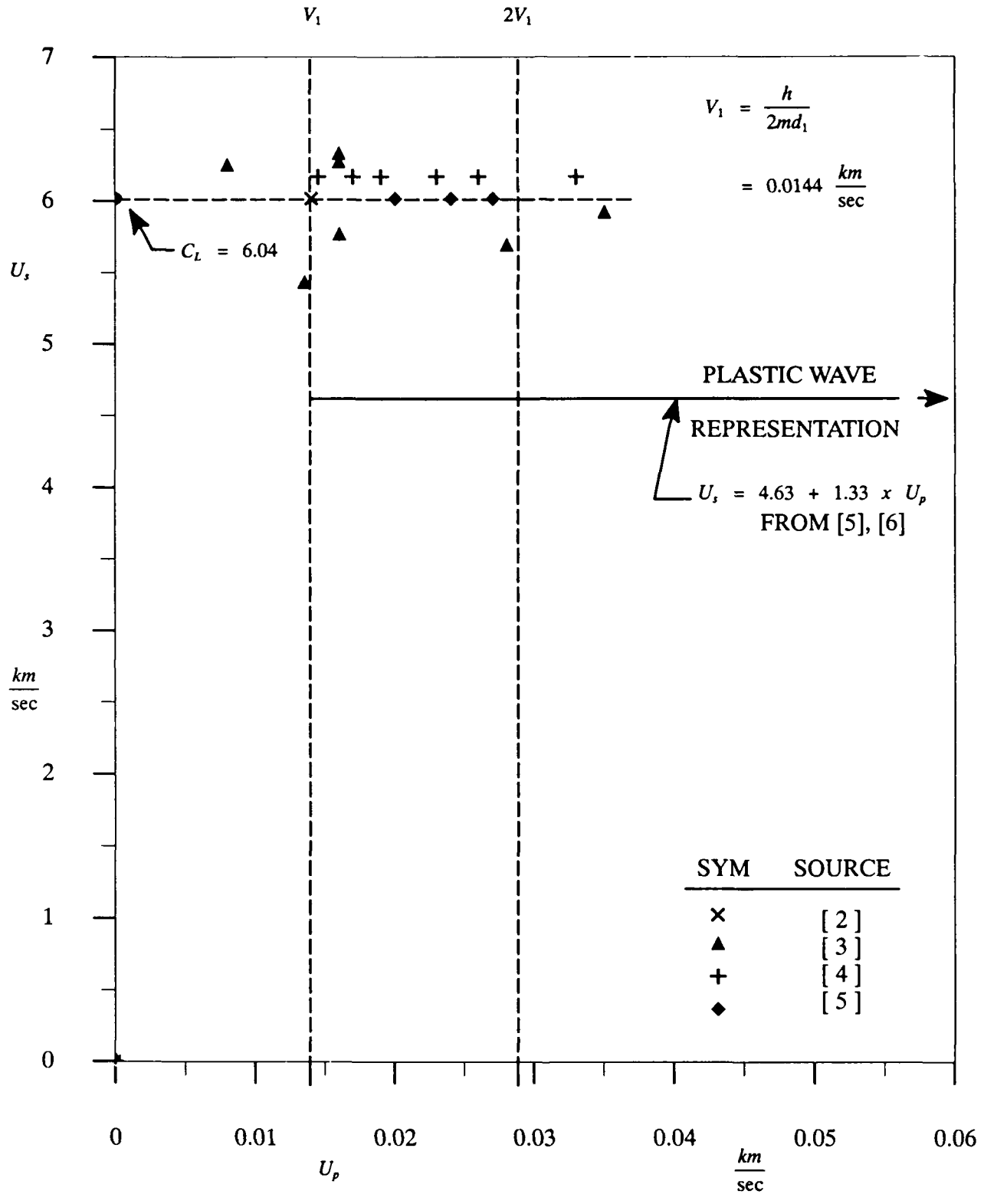

Figure 1. Elastic and Plastic Wave Front Velocity Versus Particle Velocity for Shocked Iron.

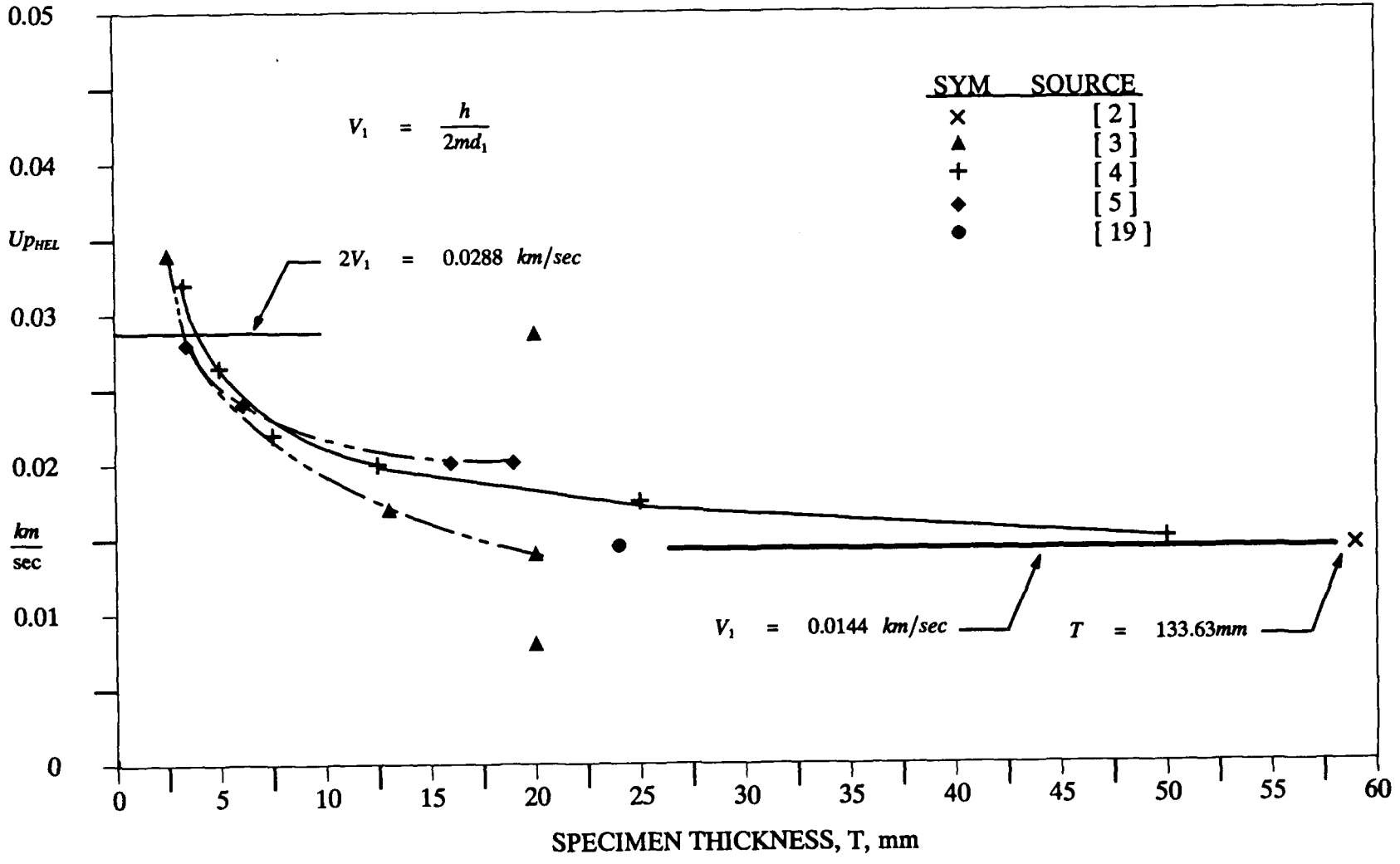

Figure 2. Elastic Wave Particle Velocity Versus Specimen Thickness for Shocked Iron.

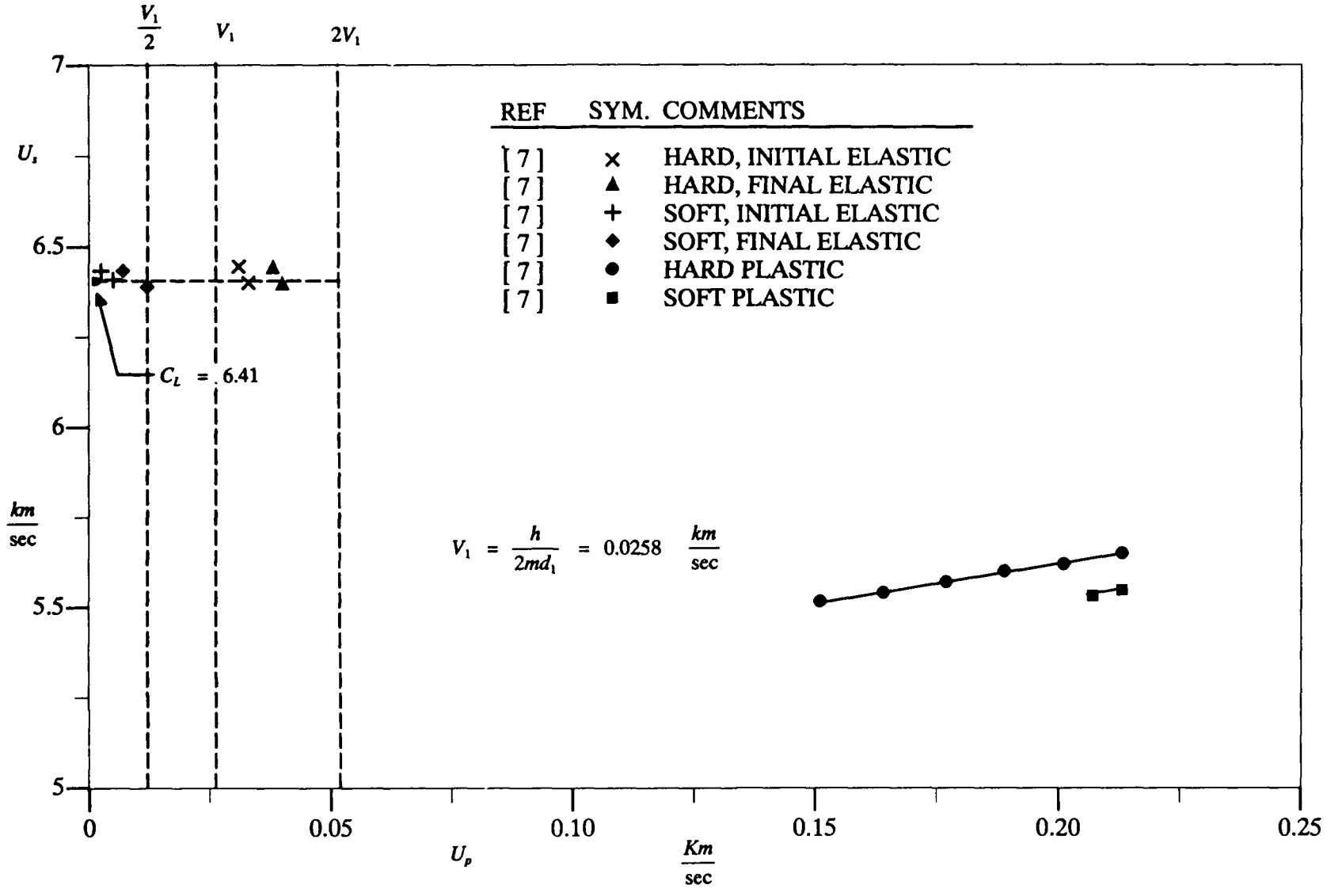

Figure 3. Elastic and Plastic Wave Front Velocity Versus Particle Velocity for Shocked 2024 Aluminum Alloy.

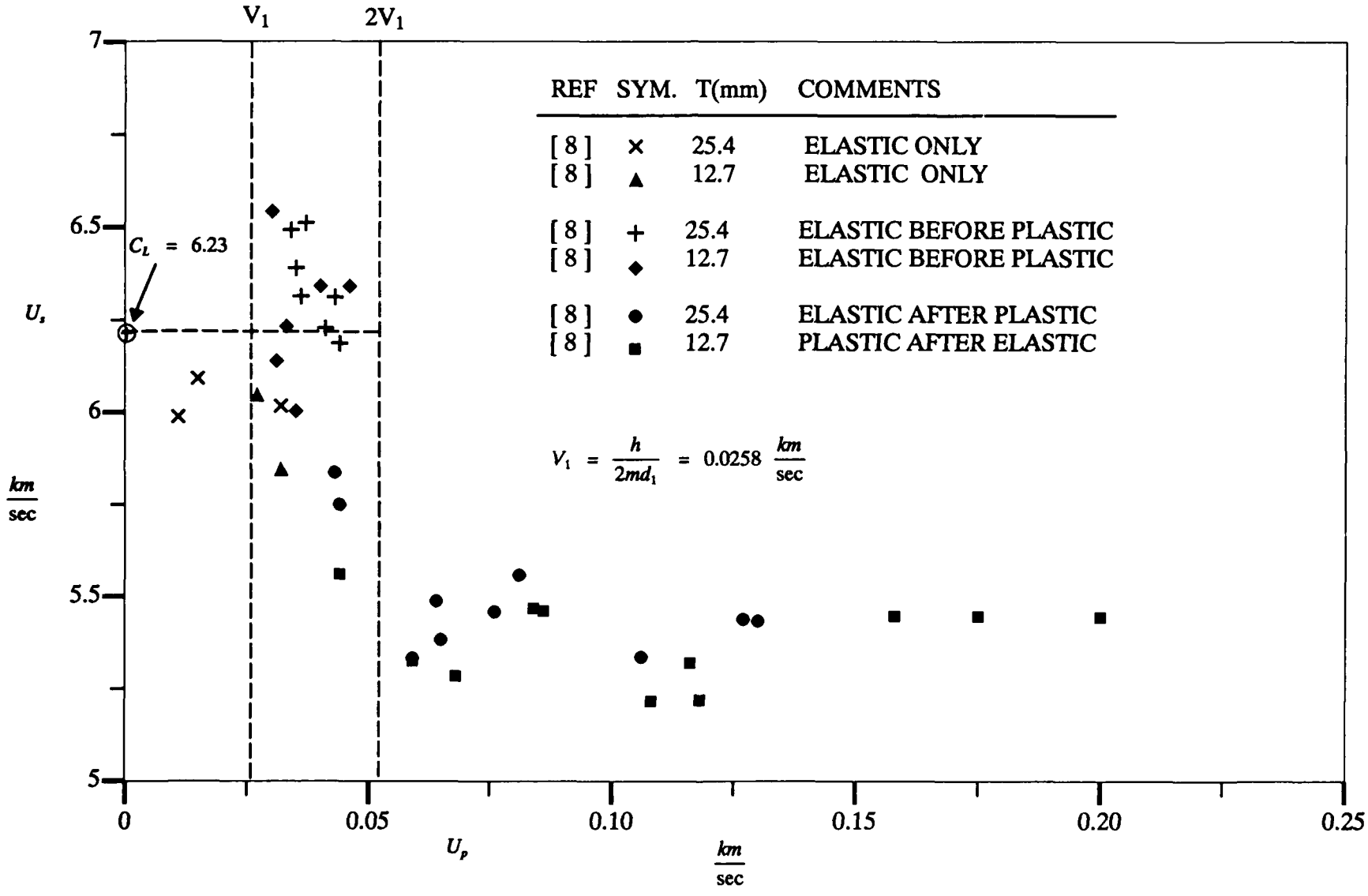

Figure 4. Elastic and Plastic Wave Front Velocity Versus Particle Velocity for Shocked 6061–T6 Aluminum Alloy.

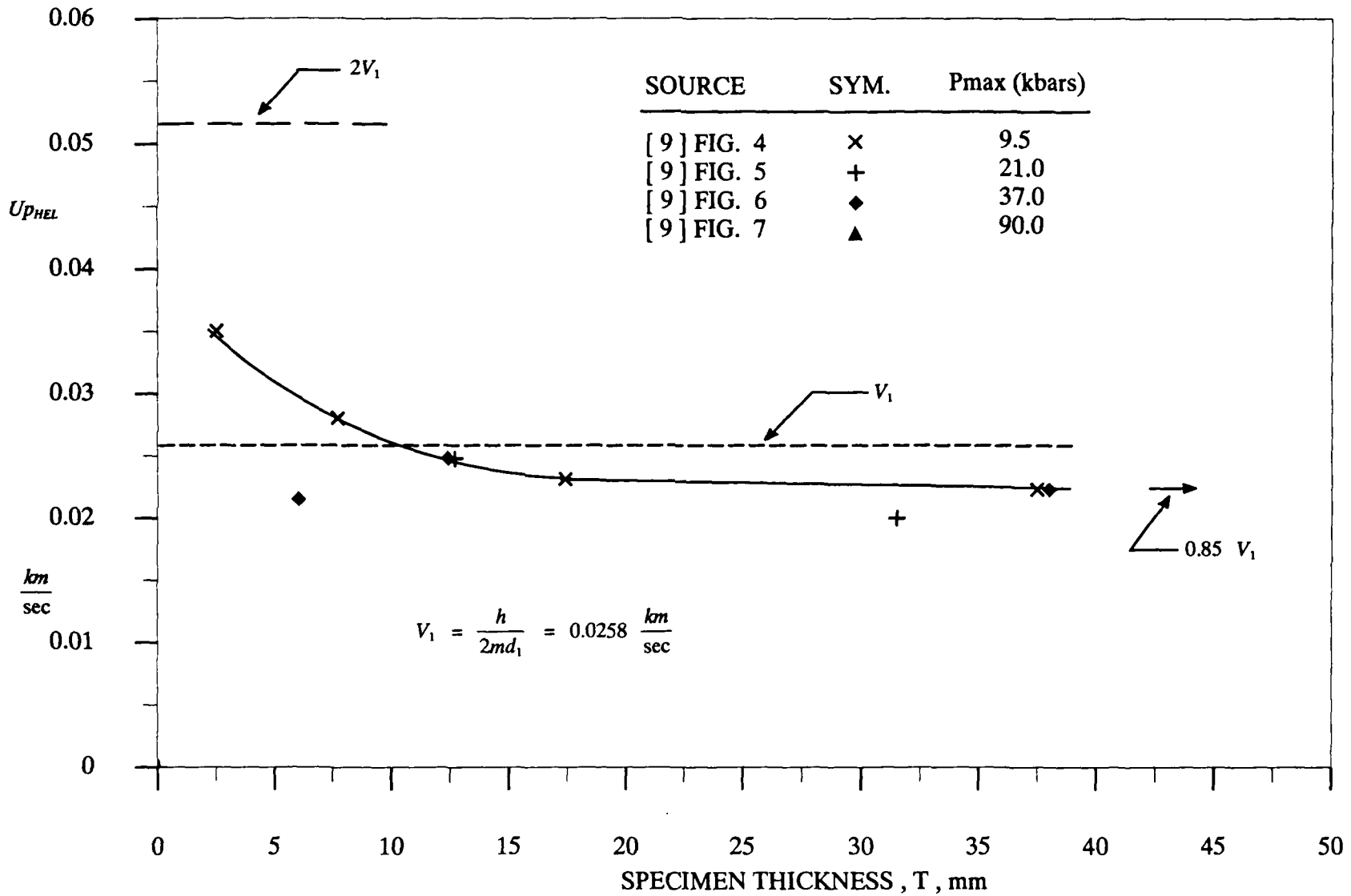

Figure 5. Elastic Wave Particle Velocity Versus Specimen Thickness for Shocked 6061–T6 Aluminum Alloy.

C. Pressed TNT

Very interesting experimental EPSP results for pressed TNT (ρo = 1.648 g/cc) are reported in Reference [10]. Elastic and plastic wave velocities are plotted as a function of their associated particle velocities in Figure 6. This figure is similar to Figure 6 of Reference [10] and Figure II–13 of Reference [11]. These EPSP data for this polycrystalline organic material exhibit metallic like behavior (see Figures 1, 3, and 4).

Only the V_1 indicator line is drawn in Figure 6 which depicts the pressed TNT EPSP wave and particle velocity experimental results from Reference [10]. Even though there is a specimen thickness size effect on both the HEL wave and particle velocities, none of the HEL particle velocities exceeded V_1. The highest value of U_{PHEL} was 0.0739 km/sec or 0.89 V_1.

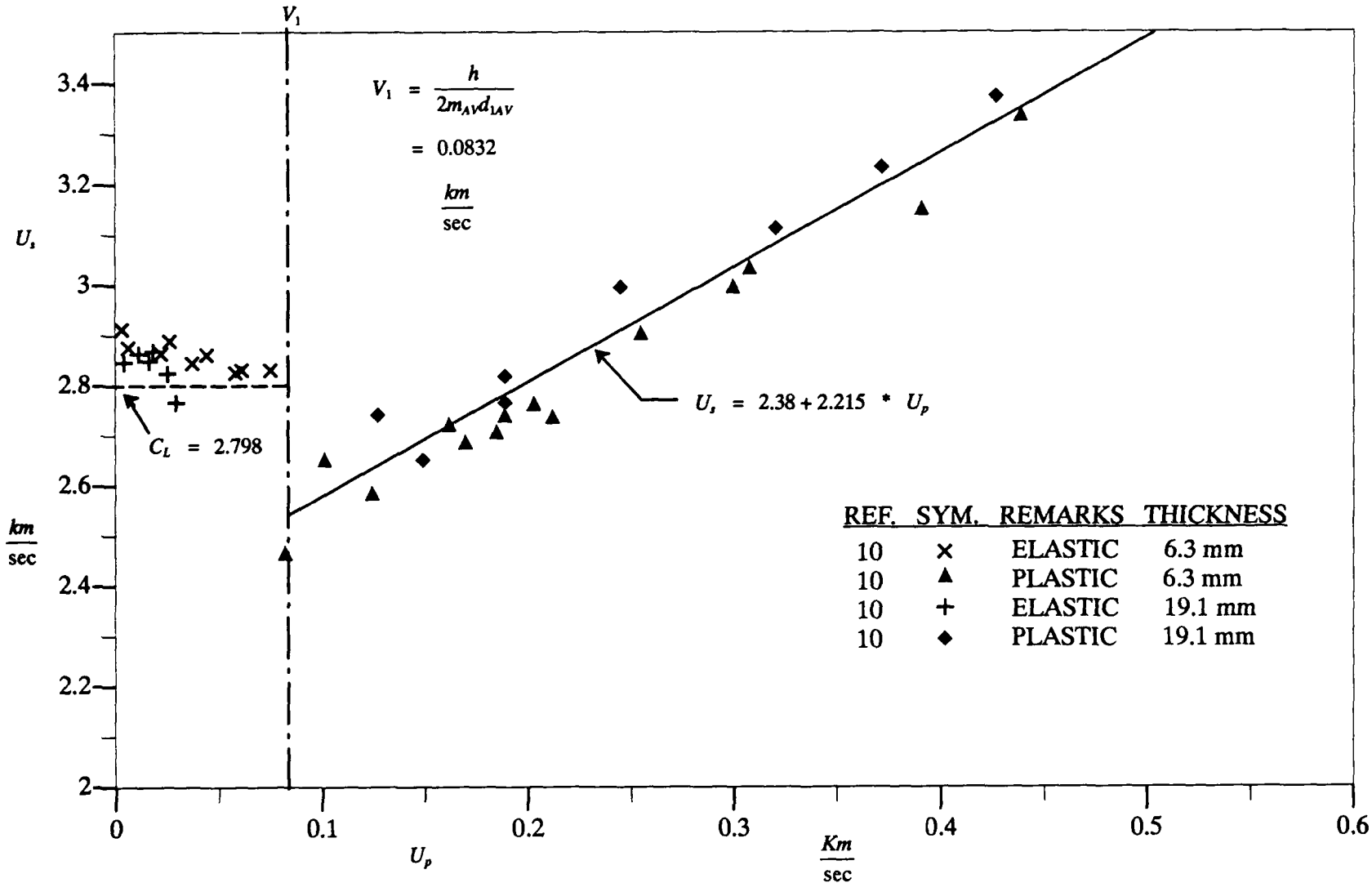

Figure 6. Elastic and Plastic Wave Front Velocity Versus Particle Velocity for Shocked TNT (ρ_0 = 1.648g/cc).

V. CONCLUSIONS

Although this is not an exhaustive investigation, enough information has been presented to indicate that:

A. A basic reason for EPSP to occur is because the De Broglie relation Eq. (1) specifies the limiting velocity (V_1) at which an atom of mass, m, can travel in an undistorted or stationary lattice structure where d_1 is the smallest distance between atoms. The plastic wave particle velocity is $Up = h/(2md_1')$ so that the lattice spacing must change from d_1 to d_1' to accommodate the irresistibility driven particle. This is a rather violent and catastrophic event whose consequences are the same as a polymorphic phase change. A phase change causes a two–wave structure since the De Broglie relation must be satisfied by adjustments made to the atomic spacing in the new lattice structure. Thus there is one wave fron the old lattice structure plus an additional wave from the new structure.

B. U_{PHEL} for the stronger metals (iron 2024–T4 and 6061–T6) was generally between V_1 and $2V_1$. Apparently strong metallic atomic lattice bonding requires that U_{PHEL} must be "overdriven " greater than V_1 to displace or distort the lattice plastically (reduce d_1 to d_1') and thus allow a plastic wave particle velocity which is $Up = h/(2md_1')$.

C. The "weak" materials (annealed 2024 alloy and pressed TNT) did not require "overdriven" HEL particle velocities for formation of plastic waves. Essentially V_1 was an upper bound on HEL particle velocities for these materials.

D. V_1 is the steady state stable U_{PHEL} for iron and 6061–T6, even when U_{PHEL} had been overdriven as much as 2.4 V_1. If sufficient time (or specimen thickness) was available, U_{PHEL} decayed and asymptotically approached V_1 as a lower bound. This is consistent with Fitzgerald's [17] stability analysis for $V_1 < Up < 2V_1$ which indicates that this is an unstable region.

E. Although U_{PHEL} magnitudes may reach 2.4 V_1 as shown for iron, most U_{PHEL} values do not exceed $2V_1$. This is consistent with Fitzgerald's analysis showing the importance and criticality of $2V_1$.

IV. RECOMMENDATIONS

Additional EPSP data for other materials should be investigated for the De Broglie velocity, V_1, influence at the HEL conditions. Certain anomalous behavior observed at low level shock loadings could possibly be explained as a V_1 effect. If this is suspected, then V_1 should be computed via Eq. (1) and compared with experimental particle velocities (Up) in the region of interest.

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